Molecular Gas Properties in the Central Kiloparsec of Barred and Unbarred Spirals

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Abstract. We study the molecular gas properties in the central kiloparsec of 29 barred and 15 unbarred spirals from the BIMA[1] Survey of Nearby Galaxies (SONG). We find that the mean nuclear molecular gas surface density of barred spirals ($\langle\Sigma_{nuc}\rangle$=309±71 $M_\odot$ pc^{-2}) is three times higher than that of unbarred spirals ($\langle\Sigma_{nuc}\rangle$=107±29 $M_\odot$ pc^{-2}). Nine out of the eleven bars with $\Sigma_{nuc} > 300$ $M_\odot$ pc^{-2} are early types. Comparison with estimates of the star formation threshold density (Σ_{crit}) indicates that enhanced star formation in bars may be due to a larger fraction having $\Sigma_{nuc} > typical$ Σ_{crit}. We also find that barred spirals are more centrally concentrated than unbarred spirals. The median value of the concentration parameter for barred spirals (f$_{con}$=$\Sigma_{nuc}/\Sigma_{disk}$=27.7) is a factor of four higher than that for the unbarred spirals (f$_{con}$=6.2). Finally we investigate the dependence of the central concentration on bar properties and find it may be weakly correlated with the bulge size, but is not correlated with the bar length. This suggests that inner Lindblad resonances, bar ellipticity and circumnuclear star formation play important roles in determining the gas accretion in the central kiloparsec.

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1. Introduction

Bars play a key role in galaxy evolution by inducing dramatic changes on relatively short time scales ($\sim 10^8$ years). Bar-induced gas mixing is known to reduce the overall metallicity gradient (e.g., Martin & Roy 1994). Three decades of observational studies show that circumnuclear starburst activity is associated with bars (e.g., Sérsic & Pastoriza 1965; Hawarden et al. 1986; Ho, Fillipenko & Sargent 1997). Models suggest that bars may be effective mechanisms for feeding active galactic nuclei (Shlosman, Frank & Begelman 1988), forming new bulges, and for evolving late Hubble type galaxies into earlier types (e.g., Friedli & Benz 1993; Norman, Sellwood & Hasan 1996). The most dramatic prediction of models is that a bar can destroy itself if sufficient mass accretes ($\sim$ 1-2%M$_{disk}$) in

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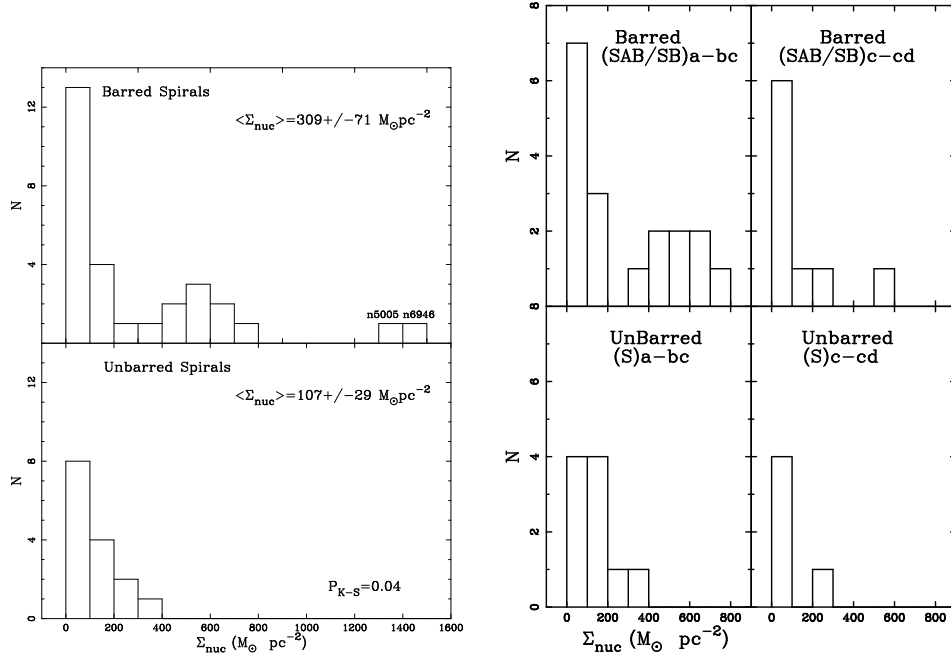[1]Berkeley-Illinois-Maryland Association

Figure 1.   **Left:** Histogram of Σ_{nuc} in barred and unbarred spirals from SONG. Note the tail of high gas surface densities in the barred spirals. **Right:** Same data now split between early (Sa-Sbc) and late type (Sc-Sd) spirals. Note that the highest gas surface densities are typically found in early type bars.

the center. Since these evolutionary changes depend not only on the gas inflow but on the gas *accretion*, we compare the gas properties of barred and unbarred spirals in the central kiloparsec (kpc); we focus on the molecular gas because it is the dominant component of the ISM in inner regions of spirals (Scoville 1990).

Though good evidence for inflowing gas has been presented (e.g., Regan, Sheth & Vogel 1999), only one study has examined whether the inflowing gas accumulates in the center (OVRO-NRO study, Sakamoto et al. 1999). This twenty galaxy sample, however, pre-selected centrally concentrated galaxies because of a CO-brightness selection criterion. Moreover, it contained only 4 late type spirals preventing comparative studies across Hubble type. Hence a study with a larger and more uniform sample is warranted. The BIMA SONG provides such a database (Regan et al. 2001). SONG consists of 29 barred spirals and 15 unbarred spirals selected as follows: $\delta > -20^o$, $i < 70^o$, $V_{HEL} < 2000$ km s^{-1}, and perhaps most importantly, $m_B < 11$.

2.   Differences in Molecular Gas Surface Density

In the left panel of Figure 1 we show the distribution of the nuclear gas surface densities (Σ_{nuc}) in the central kpc diameter region for all the SONG galaxies. The mean Σ_{nuc} for the barred spirals (Σ_{nuc}=309.1±71.3 $M_\odot$ pc^{-2}) is three times higher than that for the unbarred spirals (Σ_{nuc}=106.5±29.3 $M_\odot$ pc^{-2}). A Kolmogrov-Smirnov test shows that the distributions differ at a 96% confidence level. In the right panel, we show the same data split into early and late
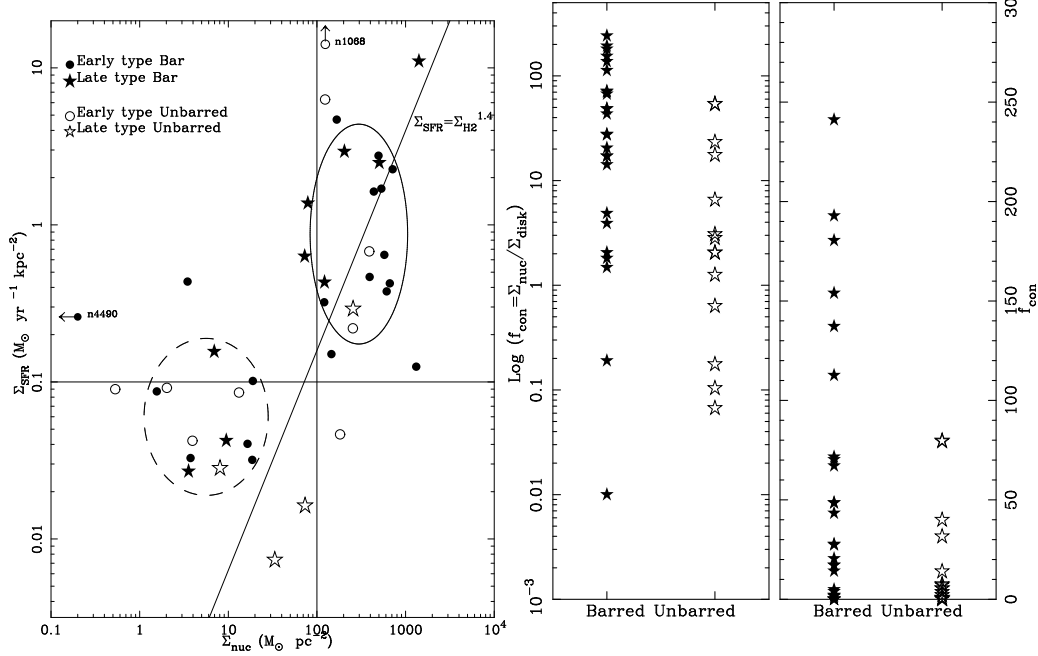
Figure 2.   **Left:** Σ_{SFR} is plotted against Σ_{nuc} for the SONG sample. The solid oval shows the high star formation rates in galaxies above the threshold density (solid vertical line) and the dashed oval shows the galaxies below the threshold. The diagonal line is the Schmidt law from Kennicutt (1998). **Right:** f$_{con}$ in barred and unbarred spirals is shown on a logarithmic (left hand box) and a linear scale (right hand box); the two distributions are distinctly different (P_{K-S}=0.07). This is strong statistical evidence for bar-induced gas inflow and accretion.

type spirals. We find that the majority of the highest Σ_{nuc} occur in early type galaxies. 9/11 bars with Σ_{nuc} >300 are early types.

These differences in Σ_{nuc} are important for understanding circumnuclear star formation activity. Using a simple gravitational instability model (e.g., Kennicutt 1989), or a magneto-Jean's instability model (e.g., Kim & Ostriker 2001), we estimate that the lower limit to the typical threshold or critical gas surface density (Σ_{crit}) is ∼100 $M_\odot$ pc^{-2}, assuming the shallowest rotation curve from Sofue et al. (1999) and lowest velocity dispersion from Galactic center measurements (Bally et al. 1988) Though Σ_{crit} undoubtedly varies from galaxy to galaxy depending on the steepness of the rotation curve and the velocity dispersion, 100 $M_\odot$ pc^{-2} is a reasonable lower limit.

From Figure 1, we see that about half of the barred (16/29 or 55%) and unbarred (7/15 or 45%) spirals have $\Sigma_{nuc} > 100$ $M_\odot$ pc^{-2}. But the highest gas surface densities in the unbarred spirals are mostly between 100–200 $M_\odot$ pc^{-2}. In fact, for $\Sigma_{nuc} > 300$ $M_\odot$ pc^{-2}, there is only 1/15 unbarred spiral, compared to 11/29 barred spirals. Considering that the threshold density is likely to be higher than 100 $M_\odot$pc−2, and in light of over three decades of studies indicating that bars, and particularly *early type* bars, host circumnuclear starbursts, we suggest that barred spirals are more prone to circumnuclear star formation because a

higher fraction have $\Sigma_{nuc} > typical\ \Sigma_{crit}$. We investigate the star formation activity in the SONG sample further in the next section.

3.   Star Formation Rates, Gas Surface Densities & the Schmidt Law

In the left panel of Figure 2, we plot the star formation rate surface density (Σ_{SFR}) against the molecular gas surface densities. Above the typical threshold value of 100 $M_\odot$ pc^{-2} (shown by the vertical solid line), we find higher star formation rates but there is considerable scatter in the data. These galaxies, mostly early-type barred bars, are indicated with the solid oval; they tend to lie along the Schmidt law (Kennicutt 1998). Below the critical density galaxies have significantly lower star formation activity (dashed oval) but it is worthwhile noting that these galaxies have higher Σ_{SFR} than would be predicted from the Schmidt law; this behavior needs further analysis. These data confirm the hypothesis in the previous section that galaxies above the thresold, i.e. barred spirals, are, on average, prone to higher star formation activity.

4.   Central Concentrations

In this section, we examine the re-distribution of the gas by the bar by calculating a concentration parameter, $f_{con}=\Sigma_{nuc}/\Sigma_{disk}$, introduced by Sakamoto et al. (1999). The results are plotted in the right panel of Figure 2. The barred spirals have a mean f_{con} of 60.22±13.6 whereas the unbarred spirals have a mean f_{con} of 21.27±7.32. A K-S test shows that the probability of the two samples being drawn from the same distribution is 7%. The SONG data confirm the basic result of Sakamoto et al. that barred spirals are more centrally concentrated than unbarred spirals. The two studies together provide solid statistical evidence for bar-induced gas transport to the central kpc.

We also find that ∼10^8 $M_\odot$ of gas must have been transported in by the bar, consistent with the OVRO-NRO data. However, the mean difference in the mass between barred and unbarred spirals in our sample is 1.7 ×10^8 $M_\odot$, smaller than the value derived by Sakamoto et al. because our sample was less biased towards centrally concentrated galaxies. As discussed in Sakamoto et al. (1999), if the mass inflow rate in bars is on the order of 1 $M_\odot$ yr^{-1}, the two studies indicate that the bar destruction time scale is at least 10^8 years, consistent with modeling studies.

5.   Bar Properties and the Central Concentration

Parameters such as the bar length (or equivalently its pattern speed), bar ellipticity, and the strength of the bulge are responsible for controlling the rate of the mass inflow. One expects that the mass inflow rate is increased whenever the bulge is small relative to the bar, the bar is thin, and the bar is long.

5.1.   Bar Length

The bar length is the most straightforward parameter to calculate. In the left panel of Figure 3, we compare the deprojected bar length, normalized by the
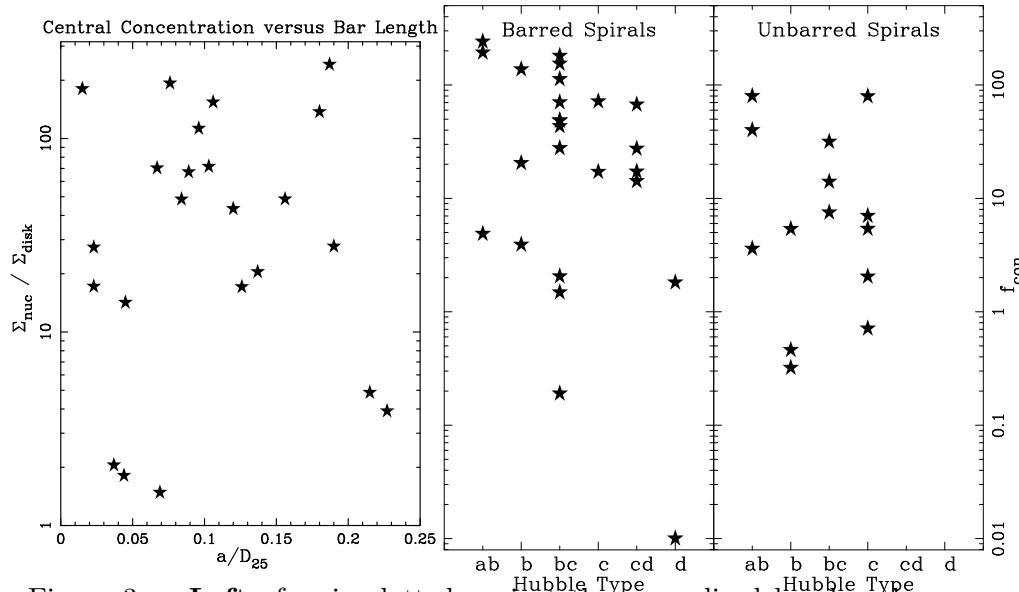
Figure 3.   **Left:** f_{con} is plotted against the normalized bar lengths $(a/D_{25}$. There is no correlation between the bar length and the central concentration of gas, implying that bar ellipticity and/or star formation are equally, if not more important. **Right:** f_{con} is plotted against the Hubble type for the barred (left box) and unbarred spirals (right box). There is a slight trend of higher central concentrations in big bulges (i.e., earlier type bars), but the trend is not statistically significant.

galaxy diameter, to the central concentrations. We find that there is *no* correlation between the bar length and f_{con}.

Since bar length is a function of the Hubble type (e.g., Elmegreen & Elmegreen 1985), we checked the relationship between f_{con} and bar length within each Hubble type bin and found no correlation. Thus we conclude that bar length alone is a poor indicator of the central mass concentrations in barred spirals. Other factors such as the bar ellipticity or the nuclear star formation rate are equally, if not more, important in determining the central gas concentration.

5.2. Bulge type

In the right hand panel of Figure 3 we compare f_{con} to the bulge size (using Hubble type as a proxy for bulge size). For the barred spirals (left box) we find that for each Hubble type (ab:b:bc:c:cd:d) the mean value of the central concentration (146:53:64:44:31:1) shows a trend of decreasing f_{con} with later Hubble types. However there is large dispersion in the sample and a least squares fit shows that the trend is not statistically significant; a larger sample is necessary to confirm the trend.

If the central concentrations are higher in earlier type bars, then the presence of inner Lindblad resonances may provide a satisfactory explanation for the trend. In models, the inflowing gas accumulates in a circumnuclear ring located between the outer and inner ILR (Sheth et al. 2000; Combes 1996). Though the typical radius of such circumnuclear rings is ~ 1 kpc (e.g., Buta & Combes

1996); however, bigger bulges have deeper potentials and hence the ILR gas ring is likely to be at smaller radii.

6.   Summary

Using a 44 galaxy sample from SONG, we found that the central kpc of bars have high molecular gas surface densities, and that a higher fraction have $\Sigma_{nuc} > typical$ Σ_{crit}; this may explain the observed enhancement in circumnuclear star formation activity in bars, particularly in early type bars. We also find that barred spirals are more centrally concentrated than unbarred spirals, confirming the role of the bar in transporting gas inwards, consistent with the OVRO-NRO study by Sakamoto et al. (1999). The central concentrations are weakly correlated with the bulge size, but not with the bar length. suggesting that ILRs, bar ellipticity and star formation play equally important roles in determining the central kpc gas properties.

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